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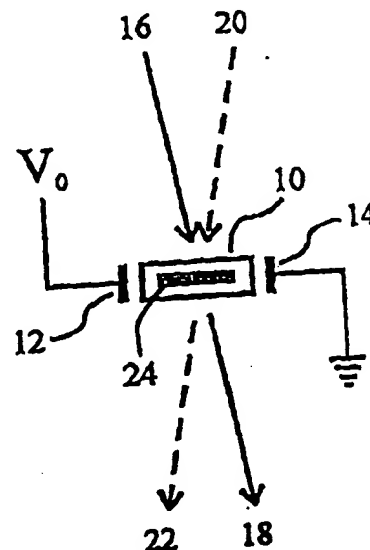
(51) International Patent Classification 6 : G03H 1/02	A1	(11) International Publication Number: WO 00/02098
		(43) International Publication Date: 13 January 2000 (13.01.00)
<p>(21) International Application Number: PCT/IL99/00368</p> <p>(22) International Filing Date: 6 July 1999 (06.07.99)</p> <p>(30) Priority Data: 125241 6 July 1998 (06.07.98) IL</p> <p>(71) Applicant (for all designated States except US): YISSUM RESEARCH DEVELOPMENT COMPANY OF THE HEBREW UNIVERSITY OF JERUSALEM (IL/IL); Jabotinsky Street 46, 92182 Jerusalem (IL).</p> <p>(72) Inventors; and (75) Inventors/Applicants (for US only): AGRANAT, Aharon, J. (IL/IL); Haaszim Street 29, 90805 Mevasseret Zion (IL). PESSACH, Benny (IL/IL); Mintz Street 14, 69512 Tel Aviv (IL). ROGEL, Larry, Rudolph (US/US); 115 Stedman Street, Brookline, MA 02446 (US).</p> <p>(74) Agent: BITAN, PEARL, LATZER & COHEN-ZEDEK; Gav Yam Center 2, Shenkar Street 7, 46725 Herzlia (IL).</p>	<p>(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).</p> <p>Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</p>	

(54) Title: ELECTRO-HOLOGRAPHIC OPTICAL SWITCH

(57) Abstract

The invention relates to an optical switch which includes a paraelectric photorefractive material (10), storing a hologram (24), possibly a latent hologram, whose reconstruction, or activation and reconstruction, is controllable by means of an applied electric field (12, 14). The hologram may be formed by spatial modulation of refractive index of the paraelectric photorefractive material, which arises from the quadratic electro-optic effect induced by the combined action of a spatially modulated space charge within the paraelectric photorefractive material and an external applied electric field. The switch may be used in a switching network, such as a multistage network for optical communication.

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interconnects which are built either of optical waveguides, such as described by S. Somekh, E. Garmire, A. Yariv, H. L. Garvin and R. G. Hunsperger, in their paper entitled "Channel optical waveguides and directional coupling in GaAs-imbedded and ridged", in Applied Optics, Vol.13, pp.327-330 (1974), or of imaging systems such as
5 that described by A. W. Lohman, W. Stork and G. Stucke, in "Optical perfect shuffle", published in Applied Optics, Vol. 25, pp.1530-1531 (1986), or of static holographic optical elements (HOE's) such as that described by R. K. Kostuk, J. W. Goodman and L. Hesselink, in their article "Design considerations for holographic optical interconnects", published in Applied Optics, Vol. 26, pp.3947-3953 (1987). However, dynamic optical
10 interconnects, which enable the dynamic reconfiguration of the connecting scheme between the source nodes and the target nodes are overwhelmingly more effective, as described in the articles in the review volume entitled "Photonic Switching and Interconnects" by Abdellatif Marrakchi, published by Marcel Dekker Inc., 1994.

The structure of a MIN is usually of alternating layers of static interconnection
15 patterns, such as the perfect shuffle described by H. S. Stone in "Parallel processing with perfect shuffle", IEEE Transactions on Computing, Vol. C-20, pp. 152-161 (1971), followed by an array of basic switching modules, known as bypass-exchange switches. The bypass-exchange switch has two inputs and two outputs with two operating states: the bypass state, in which the two input signals are directly connected to the respective
20 output ports and the exchange state, in which the input signals are crossed between the output ports.

A common optical exchange-bypass switch currently in use utilizes a Polarizing Beam Splitter (PBS) combined with a polarization control element at the input to the PBS. The polarization control element is usually a liquid crystal, or a ferroelectric liquid
25 crystal, which is faster. However, even the ferroelectric liquid crystal does not have a sufficiently fast response time for the requirements of present communication switching needs, and certainly not for future needs. Moreover, another major drawback of PBS is the high sensitivity of the cross-talk level of the switch to polarization instability of the transmitted light or the liquid crystal modulators. Consequently, the PBS cross-connect
30 switch is sensitive to the temperature and environmental stability of the modulators and of the whole system.

applied electric field. EH is based on the use of the voltage controlled photorefractive effect in the paraelectric phase, where the electro-optic effect is quadratic. Volume holograms stored as a spatial distribution of space charge in a paraelectric crystal can be reconstructed by the application of an electric field to the crystal. This field activates
5 prestored holograms which determine the routing of data-carrying light beams.

The implementation of EH based devices requires the use of a photorefractive crystal with suitable properties, such as potassium tantalate niobate (KTN), strontium boron niobate (SBN), or especially potassium lithium tantalate niobate (KLTN), as described in U.S. Patent No. 5,614,129. KLTN doped with copper and vanadium is
10 particularly suitable for use as the medium for EH devices.

EH devices can be advantageously used as the building blocks in Multistage Interconnection Networks (MIN). The MIN is composed of arrays of EH switches which can be electrically switched between one or more states. In each state a different set of holograms are activated, which direct the light beams in the required 3D directions to the
15 next stage. These switches thus contain the spatial routing information, thereby obviating the need for additional optics between the stages. The EH switch thus enables a wide variety of interconnect configurations to be implemented, with compact dimensions and for large number of nodes.

Furthermore, unlike conventional holographic memory components based on
20 conventional photorefractive crystals, which can be written and read only in the visible, the EH devices based on KLTN and similar materials can be operated in the near infra-red regions of the spectrum, including at 1.3 μ m and 1.55 μ m, wavelengths which are now commonly used in standard communication systems.

The use of EH switching technology can extend the routing capabilities of the
25 basic bypass-exchange or cross-connect switch by increasing the number of input and output ports. Consequently, the use of EH switches according to the present invention enables a significant reduction in the total number of switches required for a full access MIN, thereby significantly decreasing the system size and cost.

There is thus further provided in accordance with another preferred embodiment
30 of the present invention, an EH voltage-controlled optical switch, consisting of a paraelectric photorefractive material, wherein is stored a hologram whose reconstruction

means of electrodes on two opposite faces of the photorefractive material.

In accordance with yet another preferred embodiment of the present invention, there is provided an optical switch consisting of at least two paraelectric photorefractive crystals, in each of which is stored at least one hologram, whose reconstruction is
5 controllable by means of an electric field applied to each of the crystals. the crystals being disposed so that a light beam traverses them serially.

In accordance with a further preferred embodiment of the present invention, there is also provided an optical switch consisting of at least two paraelectric photorefractive crystals, in each of which is stored at least one latent hologram, whose activation and
10 reconstruction are controllable by means of an electric field applied to each of the crystals, the crystals being disposed so that a light beam traverses them serially.

In accordance with a further preferred embodiment of the present invention, there is also provided an optical switch consisting of at least two paraelectric photorefractive
15 crystals, as described above, and wherein each of the at least two photorefractive crystals diffracts at least one input light beam to a preselected output direction, in accordance with the at least one hologram stored therein.

In accordance with still another preferred embodiment of the present invention, there is provided an optical switch consisting of at least two paraelectric photorefractive
20 crystals, as described above, and wherein the input light beam can be switched to a preselected output direction according to the electric field applied to each of the at least two photorefractive crystal.

There is further provided in accordance with yet another preferred embodiment of the present invention, an optical switch consisting of at least two paraelectric
25 photorefractive crystals, as described above, and wherein undiffracted light is either absorbed by a light block or is inputted to a detector.

There is further provided in accordance with still another preferred embodiment of the present invention, an optical switch including a detector as described above, the switch being part of an optical switching network, and wherein the detector is used to
30 read the address header of optical data traversing the switch, and wherein the address header could be used to control the switching network.

possible states of the switch. In this switch the state is changed by flipping the applied voltages between the two crystals.

5 Figs. 3(a) to 3(c) schematically show an implementation of an EH digital switch utilizing 3 crystals, which supports a full access connection between four nodes. The three figures show the three possible cyclic permutations supported by this configuration. The selection between the three permutations is done by applying a voltage to one of the crystals.

10 Fig. 4 is a schematic representation of the optical system used for writing the holograms on the three crystals of a 4-node digital EH bypass-exchange switch. This system is used in the production stage of the switch, and the figure shows a number of computer controlled elements of the writing system, in order to make the process speedy and automatic, for high volume production.

15 Fig. 5 schematically shows the architecture of a switching network constructed with 4-node digital EH cross-connect switches. The network is shown connecting 4 PC computers by means of 1.2 Gbit/s optical fiber communication links.

20 Fig. 6 is a schematic illustration of a large scale MIN, constructed from an array of 4-node EH digital switches, providing full access switched connection between 64 nodes. The network is shown interconnecting 64 fiber optic data channels operating at 2.5 Gbit/sec.

25 Fig. 7 shows a digital EH switch including a detector for reading the address header of optical data batches traversing the switch, to ensure that the data is switched to its intended destination.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

30

Reference is now made to Figs. 1(a) and 1(b), which illustrate schematically the

paraelectric phase", published in Journal of the Optical Society of America B, Vol. 14, pp. 2043 - 2048 (1997)

In the paraelectric phase, the efficiency of these effects can be controlled by applying an external electric field on the crystals during the reading (reconstructing) stage.

In general, the diffraction efficiency is proportional to the local photoinduced changes in the index of refraction ($\delta(\Delta n)$). In the paraelectric phase, the electrooptically induced modulation of the index of refraction depends quadratically on the polarization and is given by:

10

$$\Delta n(r) = (1/2) n_o^3 g [P(r)]^2 \quad (1)$$

where $\Delta n(r)$ is the induced change in the index of refraction, n_o is the refractive index, g is the quadratic electrooptic coefficient, and P is the low frequency polarization. When a space charge field $E_{sc}(r)$ is formed in the crystal, the modulation which it induces in the index of refraction, and which contributes constructively to the diffraction is given by:

15

$$\delta(\Delta n(r)) = n_o^3 g \epsilon^2 E_o E_{sc}(r) \quad (2)$$

assuming that the polarization is in the linear region $P = \epsilon E$, where ϵ is the dielectric constant, and $\epsilon = \epsilon_o \epsilon_r$, and close to the phase transition $\epsilon_r \gg 1$, and E_o is the externally applied field.

It can thus be seen that the information-carrying space charge field is transformed into a modulation of the refractive index only in the presence of an external electric field. Therefore, the use of the quadratic electrooptic effect enables analog control of the efficiency of the reconstruction of the information. This is known as the voltage controlled PR effect.

25

In terms of the applied field, the diffraction efficiency of plane phase transmission holograms stored in the paraelectric phase is given by:

30

order to improve the performance of the crystal, prior to writing the holograms, the crystals are subjected to a poling process in which they are gradually cooled at 0.5°C/minute from 40°C to 10°C under an external field of 2.1kV/cm, and then warmed-up to the operational temperature at the same rate. During operation, the crystal
5 is held at 32°C, which is 6°C above its phase transition temperature, well within the paraelectric phase. The temperature is maintained by means of a stabilized thermoelectric element 24 in juxtaposition to the crystal, as shown in Fig. 1(a). For reasons of clarity, the element has been omitted in the rest of the figures.

The embodiment of the simple EH switch shown in Figs. 1(a) and 1(b) can be
10 used in many MIN architectures in place of the previously used ferroelectric or liquid crystal Polarizing Beam Splitter (PBS) switches. The EH switch is controlled by applying voltage directly to the crystal, instead of rotating the light polarization at the entrance of each switch, as for the PBS switch. A major advantage of the EH switch is that its switching time is much faster than the slow response time of the previously
15 available liquid crystal devices, even of the ferroelectric type. The measured switching time of a KLTN EH switch according to the present invention is of the order of 100nsec, but it would appear that this is a limit of the measurement equipment, and that actual switching speeds are even faster. Such switching times are very short compared to the other switching technologies currently used for free space optical switching, such as the
20 above-mentioned LCD devices. The very short switching time is a cardinal advantage of the KLTN EH switch, which makes this technology so advantageous for use in switching networks. These switching times are clearly suitable for circuit switching applications and even close to the speed required to support packet switching.

However, like the PBS switch, the simple EH bypass-exchange switch suffers
25 from the same problem of high sensitivity of the cross-talk level to polarization error of the incoming light. In the EH switch, the cross-talk arises from the polarization dependence of the diffraction efficiency, due to the difference of the quadratic electro-optic coefficients for the two polarizations. Another drawback of the simple EH switch configuration is the need to achieve as close as possible to 100% efficiency of the
30 thick hologram to eliminate the cross-talk. Thus, for example, if only 99.9% diffraction efficiency is achieved, the 0.1% of the signal which is transmitted undiffracted leads to a

miniature computer controlled linear stages 85, 86, 87, schematically shown by the arrows indicating the crystal motion. These stages are used for sliding each crystal into and out of the writing beams, to allow each crystal to have its own specific holograms written in separately. The three linear stages are mounted on a thermo-electric heater/cooler 92, to stabilize the temperature. The crystals used in the switch module
5 according to this embodiment of the present invention are 3mm x 3mm x 3mm in size, and are cut along the [100] crystallographic directions. Two gold electrodes are sputtered on the horizontal facets perpendicular to the optical axis, for applying the voltage. The crystals are gripped with miniature clamps, allowing for easy and rapid exchange of the
10 crystals. The clamps have electric contacts to the gold electrodes, but are isolated from the linear stage by a small ceramic plate, so that high voltages can be applied to the crystal without shorting. The ceramic plate also provides good thermal contact to facilitate thermal stabilization of the crystals. The high voltage power supply 88 is controlled by means of commands sent from the central computer 90. This computer also
15 controls the motion stages.

The KLTN crystals are coated with an anti-reflective coating, because of their high index of refraction ($n=2.1$). A half wavelength layer anti-reflective coating of either MgF_2 or SiO_2 is typically used. Both coatings reduce the reflection from about 12% to 0.2% at a wavelength of $\lambda_r = 1.3\mu m$ and an angle of 10° from the perpendicular to the
20 coated face.

When writing, the light from a frequency-doubled, diode-pumped Nd:YAG laser 100 ($\lambda=532nm$) is passed through a computer controlled shutter 102 and then split by means of beam splitter 104 into two vertically polarized plane wave beams, each of about 20mW. These two beams are used to write the planar phase transmission
25 holograms on each crystal. Each of the beams is reflected from mirrors mounted on computer controlled rotation stages 106, 108, having 0.005° angular accuracy, into its own 4f imaging system 110, 112, each of which images its own mirror onto the crystal. Thus, rotation of the mirror changes the angle of incidence of the beam on the crystal accordingly. The 4f imaging systems are needed for keeping the beam collimated. Each
30 4f system is constructed of two symmetric doublets 114, 118 and 115, 118 of 3" focal length each. The two beams are combined in the middle of the 4f imaging system using a

channels. Each computer is thus connected with 2 fibers to the cross-connect switch system 128, a single-mode fiber 130 which transmits the light into the switch, and a 50/125 multimode fiber 132 which receives the light from the switch. Collimating lenses are required to couple between the switch ports and the fibers, but are not shown in the drawing for clarity. The transmitter fiber should preferably be a polarization maintaining fiber, in order to maintain the optimal holographic efficiency.

The switch is controlled using a fifth computer 134 with a D/A board. The analog output of this board controls a switching module 136 containing three high voltage, high speed semiconductor switches, for switching the required $\pm 700V$ from a power supply 138 to each of the three crystals in the switch 140.

An important advantage of the digital EH switch configuration is the ability of a single switch to route k channels instead of the case of only $k=2$ channels for the simple analog EH switch. This feature is utilized when the switch is placed into the MIN. The minimal number of layers in a full access MIN is given by:

$$L = \log_2 N \quad (7)$$

where N is the number of nodes. The minimal overall number of required switches in a full access MIN is given by:

$$S = \frac{N}{k} L = \frac{N}{k} \log_2 N \quad (8)$$

Therefore, it can be seen that the number of layers and the overall number of required switches decrease dramatically with k . Furthermore, k can be used to adjust the number of possible permutations which the network can perform, or the number of degrees of freedom, according to the demand and the required cost.

A digital EH switch which is capable of handling k routes, can be made of m adjacent crystals, where each crystal contains k holograms. Each of the m crystals performs one of the m required permutations of the k routes. The condition on the required number of crystals m in a single k routes switch which is a part of a minimal

address. The preferred method is to send a header with each batch of data on the optical channel, which includes the address, similar to the system used, for example, in ATM. This method requires the delivery of a sample of the light at the input of the system to an optical detector. In the above suggested preferred embodiment of the architecture of the digital EH switch, the non-diffracted light is blocked and rejected, in order to eliminate cross-talk. If this block is replaced, however, by an optical detector, communication information such as the header can be read and used to control the switch state accordingly.

Fig. 7 shows a digital EH switch according to another preferred embodiment of the present invention, including a detector 152 for reading the address header of optical data batches traversing the switch. The header address information is conveyed to a processing unit 154 for providing the correct control signals for the switching network, to ensure that the data is switched to its intended destination. The other components are as in Figs. 2(a) and 2(b).

The combination of the digital EH switch with WDM technology can enlarge the possible architectures very significantly, and improve the resulting performance. Due to the high selectivity of thick holograms, additional holograms can be added, for the additional wavelengths, on the same switches. Those holograms can direct the different wavelengths to arbitrary directions. Thus, each wavelength in the WDM channel can be routed dynamically through a different path in the MIN and be sent to any other node. An attractive option is to use the wavelength change of adjustable wavelength laser diodes, which can be changed within 1nsec, to make a very fast cross-connect switch out of a limited set of connections which themselves can only be changed more slowly (i.e. 100 nsec) using the EH effect.

It will be appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of various features described hereinabove as well as variations and modifications thereto which would occur to a person of skill in the art upon reading the above description and which are not in the prior art.

photorefractive material is a crystal of doped Potassium Lithium Tantalate Niobate.

8. An optical switch according to any of the above claims, and wherein said electric field is applied by means of electrodes on two opposite faces of said photorefractive material.
9. An optical switch comprising at least two paraelectric photorefractive crystals, in each of which is stored at least one hologram, whose reconstruction is controllable by means of an electric field applied to each of said crystals, said crystals being disposed so that a light beam traverses them serially.
10. An optical switch comprising at least two paraelectric photorefractive crystals, in each of which is stored at least one latent hologram, whose activation and reconstruction are controllable by means of an electric field applied to each of said crystals, said crystals being disposed so that a light beam traverses them serially.
11. An optical switch according to either of claims 9 and 10, and wherein each of said at least two photorefractive crystals diffracts at least one input light beam to a preselected output direction, in accordance with the at least one hologram stored therein.
12. An optical switch according to any of claims 9 to 11, and wherein said input light beam can be switched to a preselected output direction according to the electric field applied to each of said at least two photorefractive crystal.
13. An optical switch according to any of claims 9 to 12, and wherein undiffracted light is absorbed by a light block.
14. An optical switch according to any of claims 9 to 12, and wherein undiffracted light is inputted to a detector.
15. An optical switch according to claim 14, said switch being part of an optical

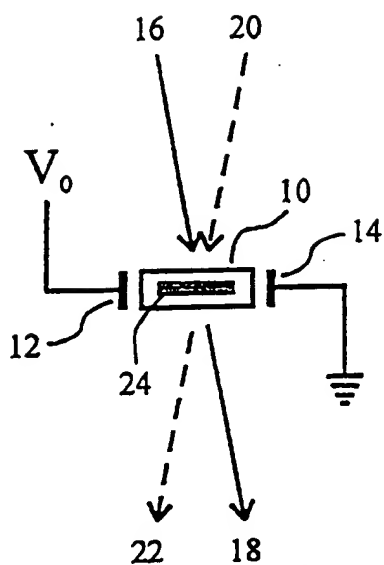


Fig. 1(a)

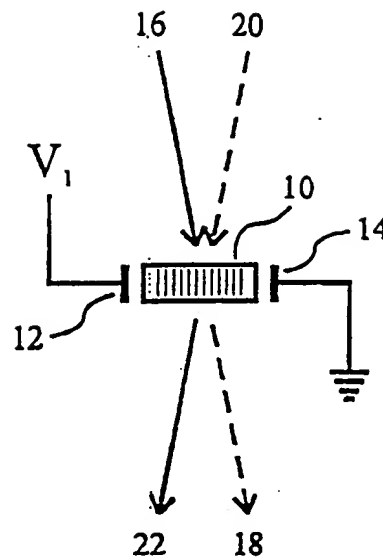


Fig. 1(b)

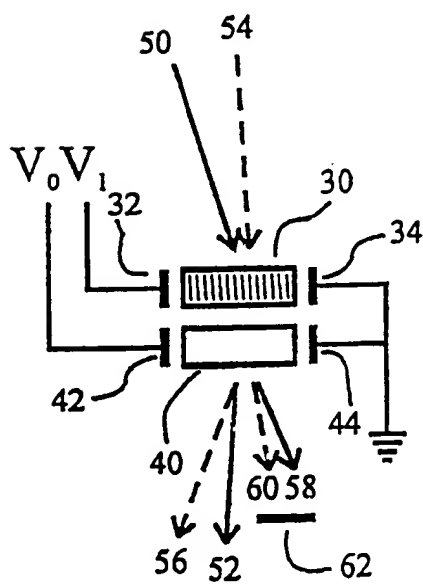


Fig. 2(a)

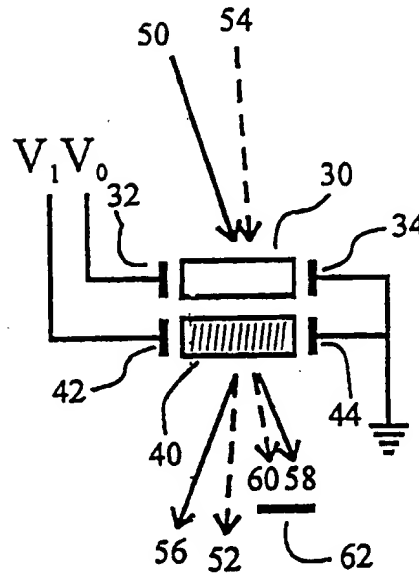


Fig. 2(b)

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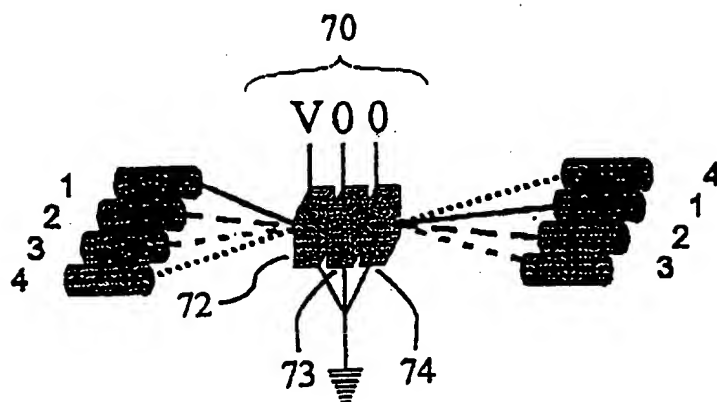


Fig. 3(a)

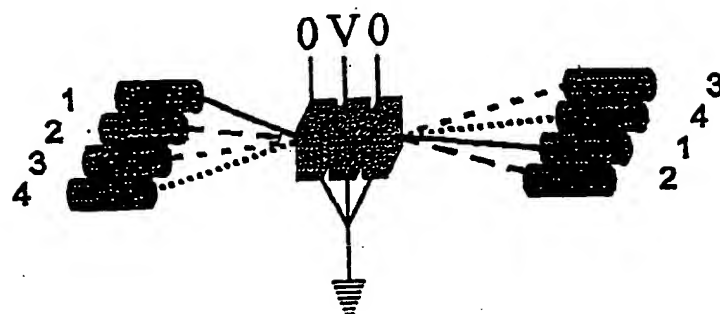


Fig. 3(b)

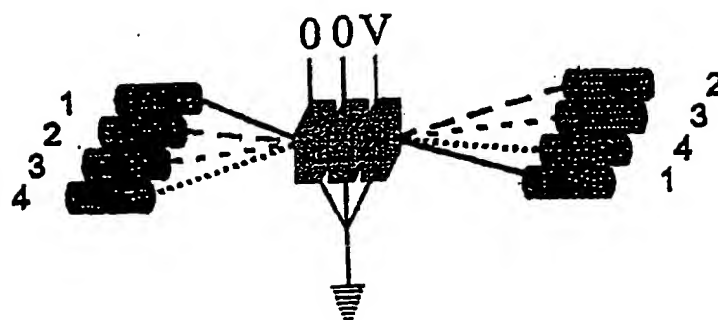


Fig. 3(c)

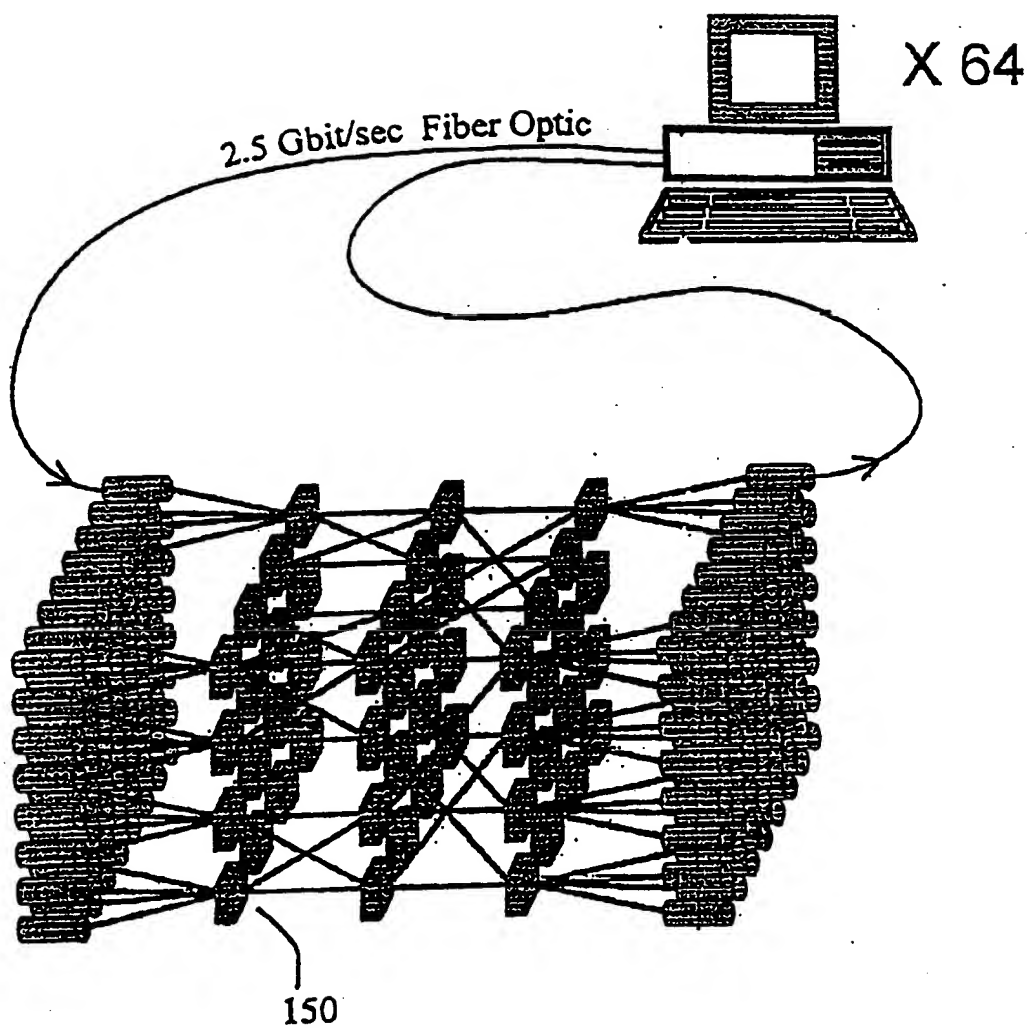


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL99/00368

Box I Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 5-8 and 12-21
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.